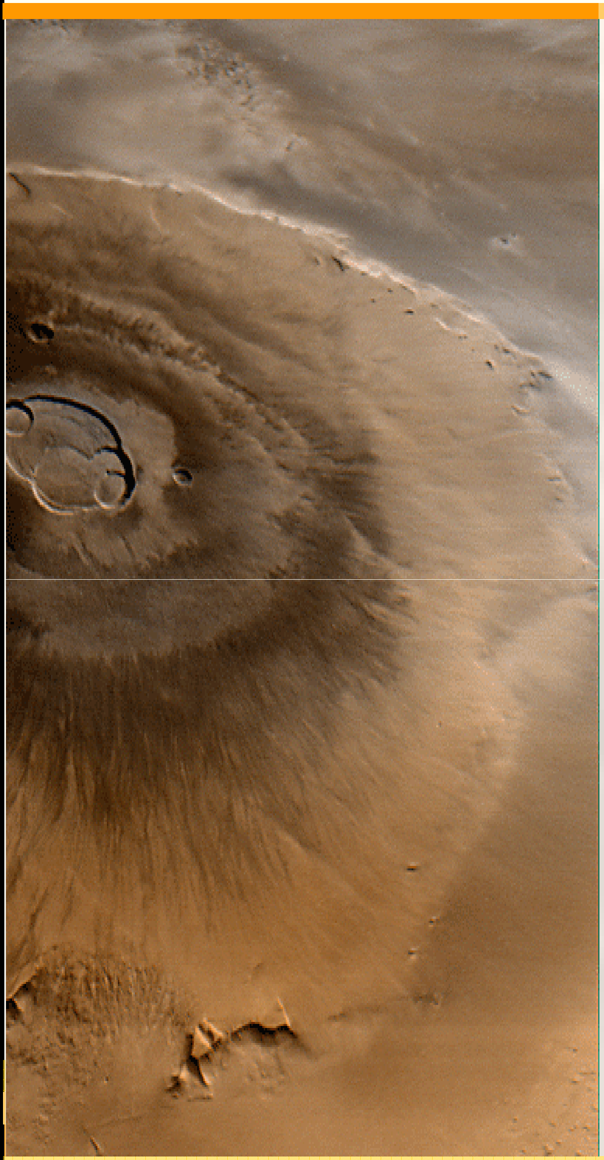

8th INTERNATIONAL PLANETARY PROBE WORKSHOP
Portsmouth, Virginia on June 6-10, 2011

EUROPEAN GNC TECHNOLOGY DEVELOPMENT AND PERSPECTIVES FOR AIRLESS BODIES EXPLORATION

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Lecture content

- Introduction
- GNC perspective of an airless body mission
- GNC roadmap and development status
- Summary and conclusions

Introduction and objective

- ESA Science and Exploration Programmes include:
  - Lunar Lander
  - Planetary moons
  - Mission to asteroids (e.g. NEO) with or without sample return

- Summary of the lecture
  - Industrial perspective of Guidance, Navigation and Control (GNC) technology for airless body missions
  - European capabilities and maturity status are presented
  - Survey is not meant to be exhaustive but detected relevant capability in LSI, medium, SME and Research Centers.
  - Innovation in methods and techniques as well as GNC solutions development
  - Gap analysis aimed to identify the future needs and strategies to reduce cost and time towards mission implementation decision.

- Acknowledgment to ESA for the information provided on GNC technology developments status and roadmap

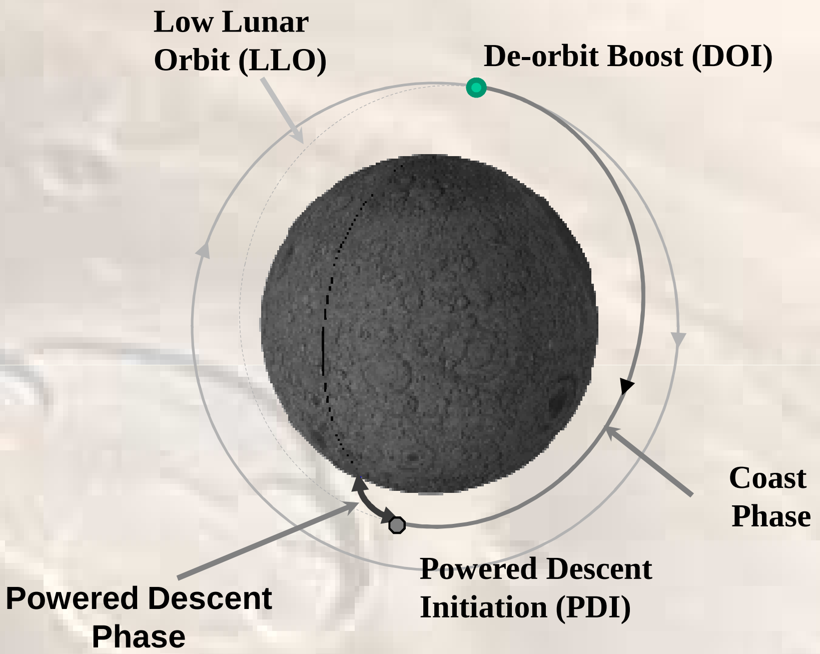
GNC perspective of an airless body mission

Airless body mission characteristics

- Mission to airless bodies can be clustered under a set of similar GNC requirements and drivers (D&L Phase):
  - The absence of atmosphere represents the major difference with respect to EDL GNC.
  - GNC must autonomously and safely reduce the arrival or orbital velocity down to values compatible with landing system dynamics.

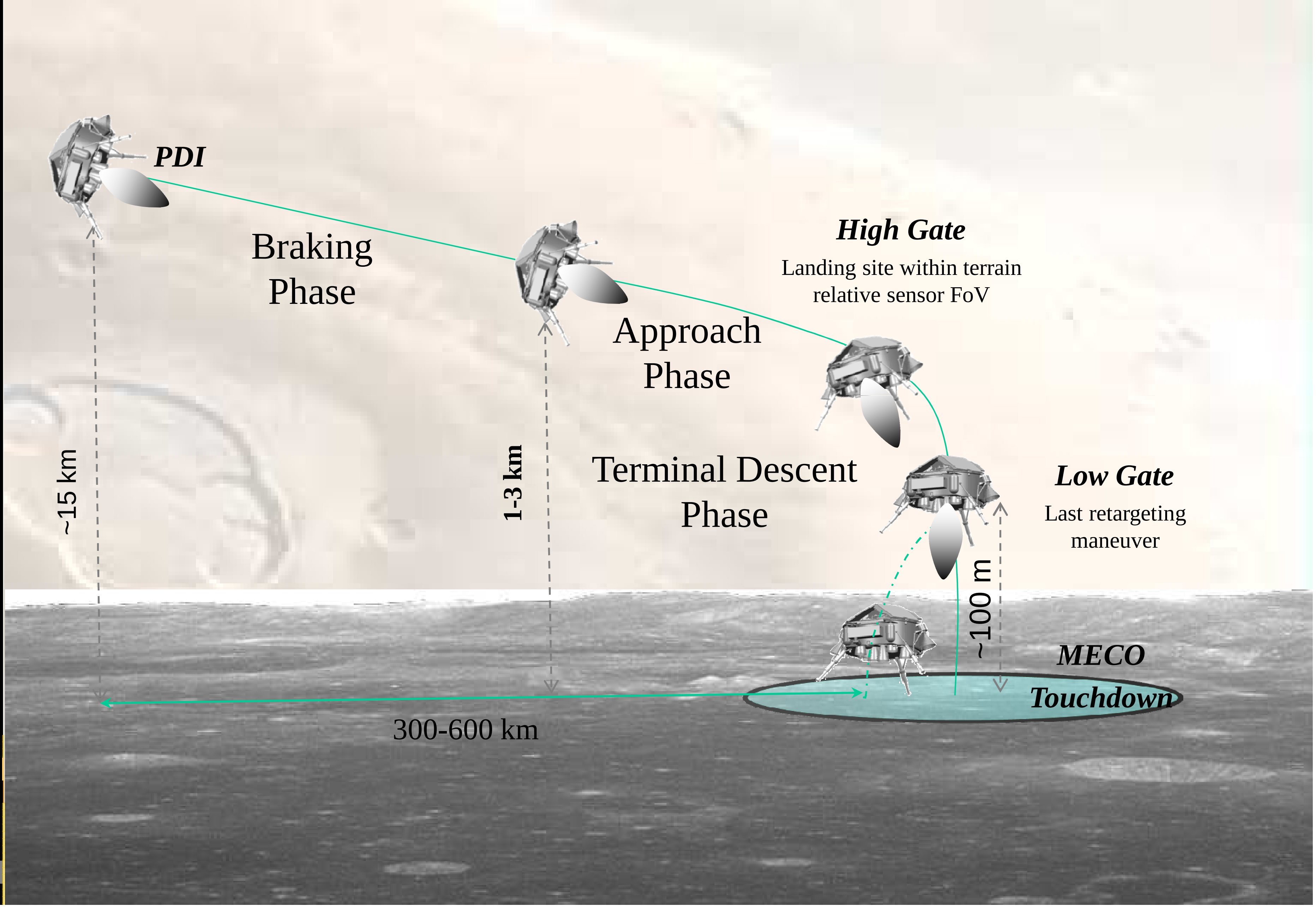
- Within airless body missions
  - Distinction between mission to major and minor bodies drives the strategy for mission design and D&L dynamics
  - The chain of nominal and off-nominal GNC modes depends on the expected operations:
    - approach for rendezvous and orbiting
    - Descent and landing phase
    - Intentional impact (e.g. NEO deflection missions)
    - Planetary body departure for sample return missions.

Reference mission: ESA Lunar Lander programme



Trajectory Phase	Typical Duration
Low Lunar Orbit (LLO)	
Coast	50-60 min
Braking	10-15 min
Approach	2-3 min
Terminal Descent	< 0.5 min

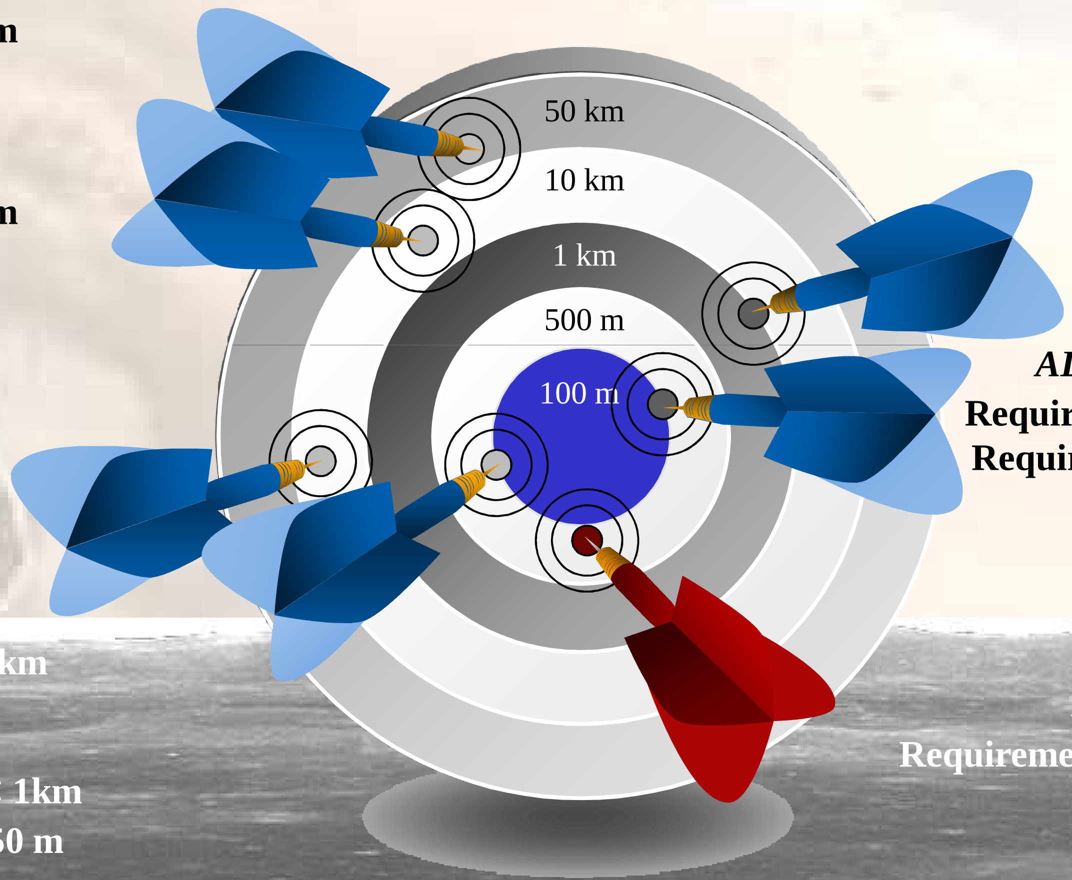
Lunar Lander: Descent & Landing Scenario



Lunar Lander: accuracy goal

Surveyor 1
Requirement: < 40 km
Achieved: ~ 19 km

Surveyor 3
Requirement: < 15 km
Achieved: ~ 3 km



ALTAIR / ALHAT
Requirement (safe) < 1 km
Requirement (safe) < 100 m

Apollo 11
Achieved (safe): ~ 7 km

Apollo 12
Requirement (safe): < 1km
Achieved (safe): ~ 150 m

MoonNext
Requirement (safe): < 200 m

Landing Accuracy Requirements

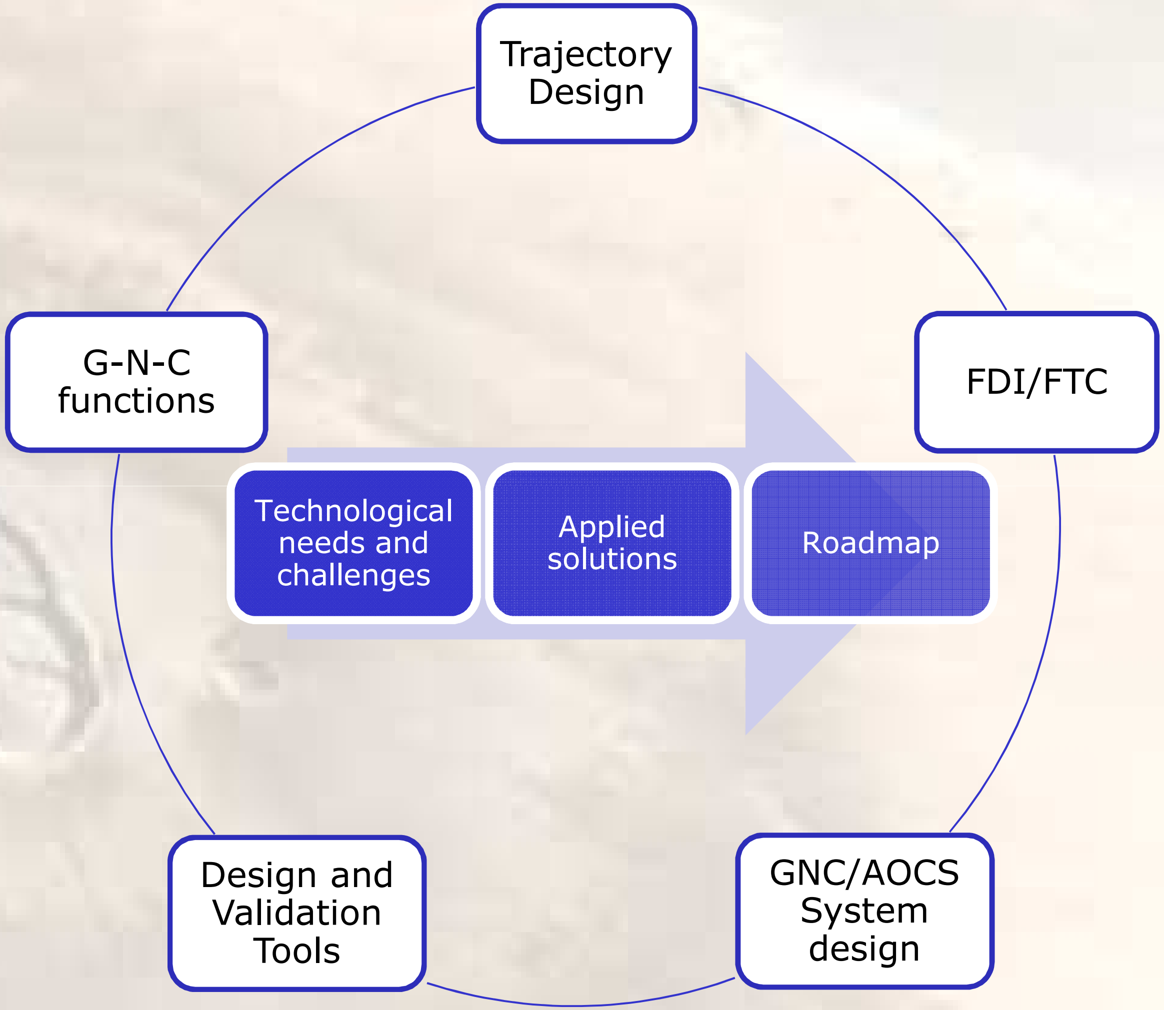
GNC roadmap and development status

GNC Technology issues and roadmap

- GNC design issue:
  - Achieving a design implementing heterogeneous, short duration and fast dynamics phases through a robust combination of on-board functions
  - Optimized and complementary equipment set
  - Need to contain the uncertainties/risk associated to the selection of technology at different TRLs

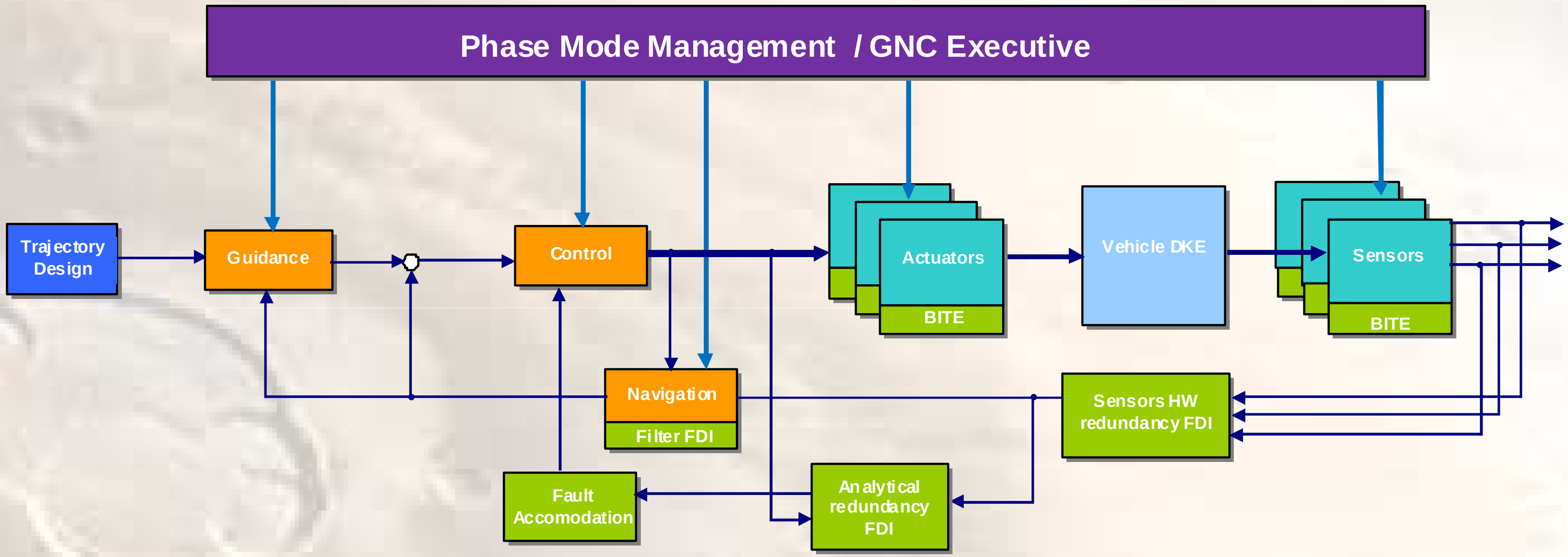
- GNC Roadmap guidelines
  - Mission and GNC design as a multidisciplinary problem
  - Adopt innovative solution for GNC methods and techniques since initial design stages
  - Focus investment on critical technology that need to be matured on time with respect to programme phases
  - Use validates models tools, testbench and facilities

GNC roadmap implementation



GNC roadmap implementation

- GNC/AOCS Functional Scheme



GNC roadmap implementation

- Combination of action in two perpendicular directions:
  - Explot results from Innovation and research activities
  - Engage into Critical GNC technology developments

GNC roadmap implementation

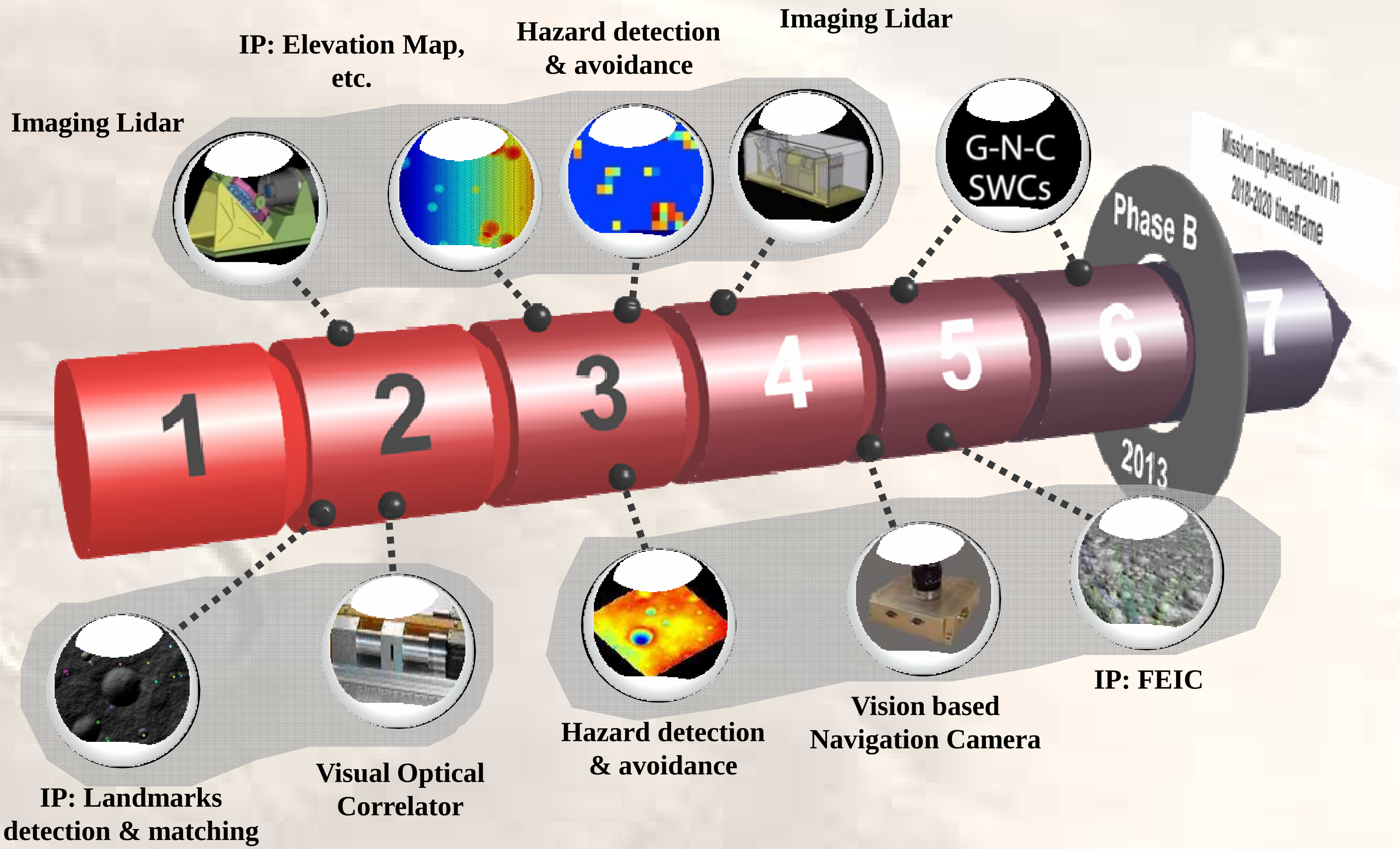
- Innovation and research activities
  - GNC Design and Analysis Methods
    - Multidisciplinary optimisation
    - Modelling Framework
    - Control Analysis and Design Framework
    - GNC control design V&V methods
  - G-N-C Algorithms and Techniques
    - Guidance schemes
    - Estimation and Filtering
    - Robust Control techniques
    - FDI / FTC *(adoption for robotic mission to be assessed)*
  - Optimum (E)DL and GNC Design

GNC roadmap implementation

- Critical GNC technology developments
  - Vision Based Navigation solution
  - Lidar based Navigation solution
  - GNC/Hazard Detection and Avoidance
  - (E)DLSimulation Frameworks
  - Synthetic planetary scene generation SW
  - Dynamic Test Facilities

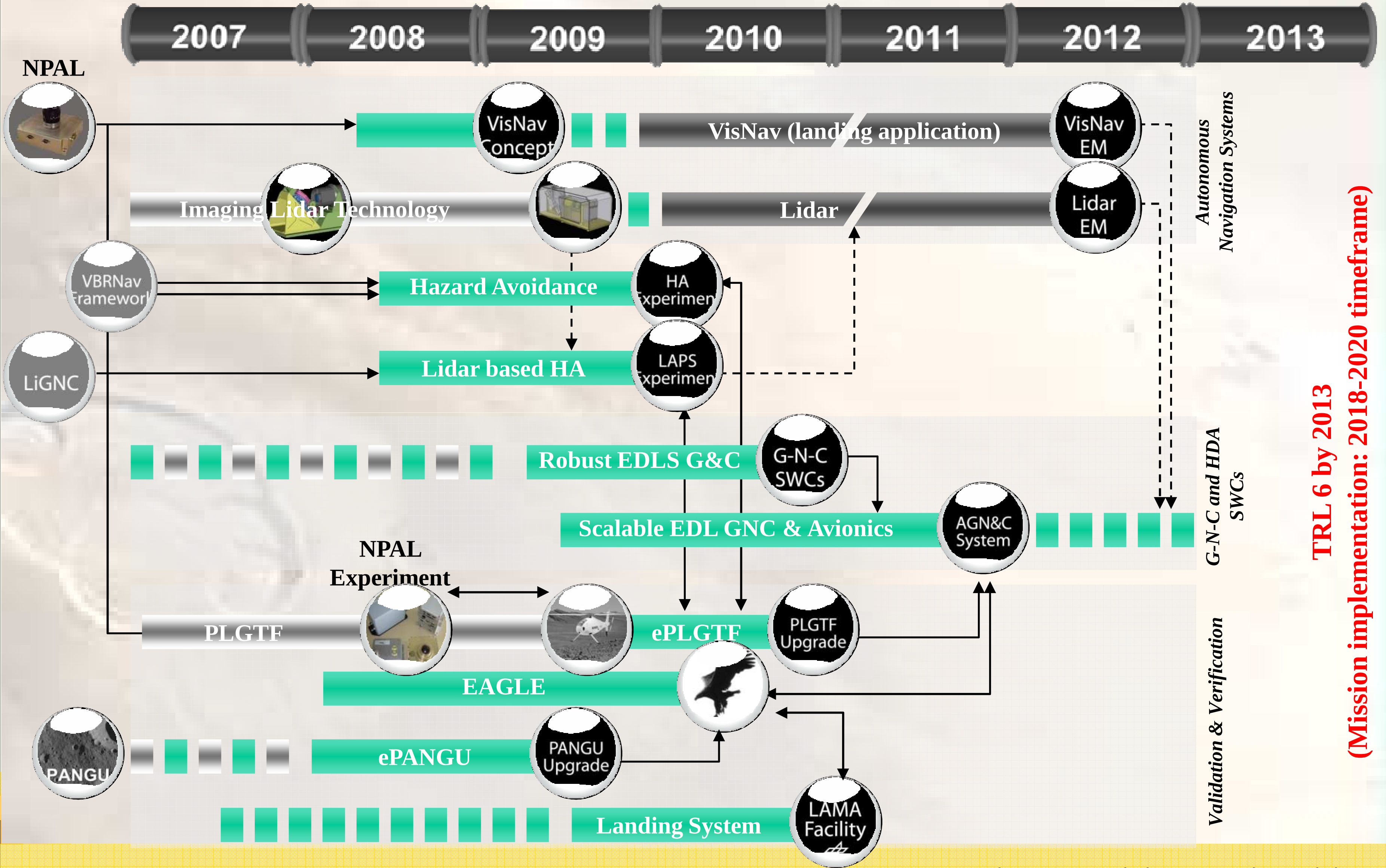
Progress and plans time-frame 2009-2013 ➔

Critical GNC technology developments



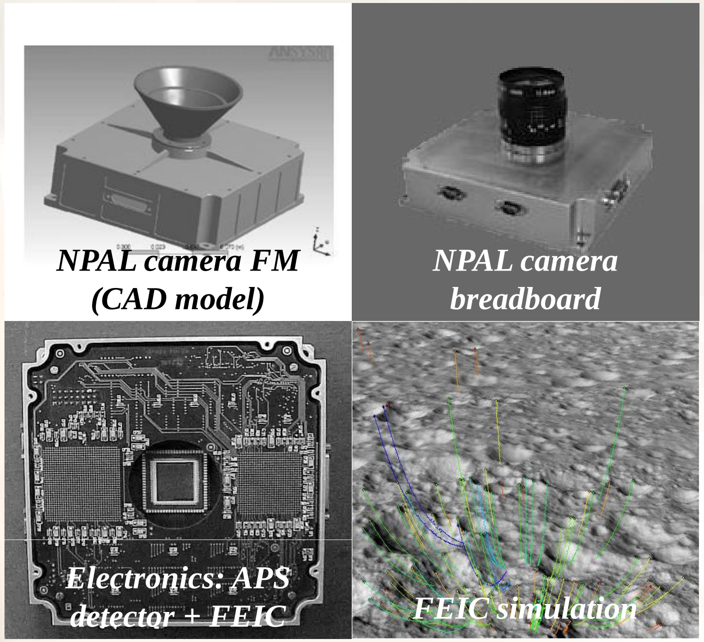
Technology Readiness Level (2009)

Critical GNC technology developments



Navigation for Planetary Approach and Landing (NPAL)

- **Background**
  - Lunar landing technology development
  - Initially conceived for Mercury lander on Bepi Colombo
- **Achievements**
  - Vision-based navigation camera breadboard, with commercial optics
  - Real-time FEIC and Navigation SW
  - VBNC flight model detailed design
  - Validation and verification simulation tools: VBNAT and PANGU
  - TRL: 4-5
- **Main features**
  - Optical navigation based on unknown feature points extraction and tracking
  - Autonomous star tracker components (APS, CPU, electronics) used for VBNC
- **Test approach**
  - PLGTF field tests



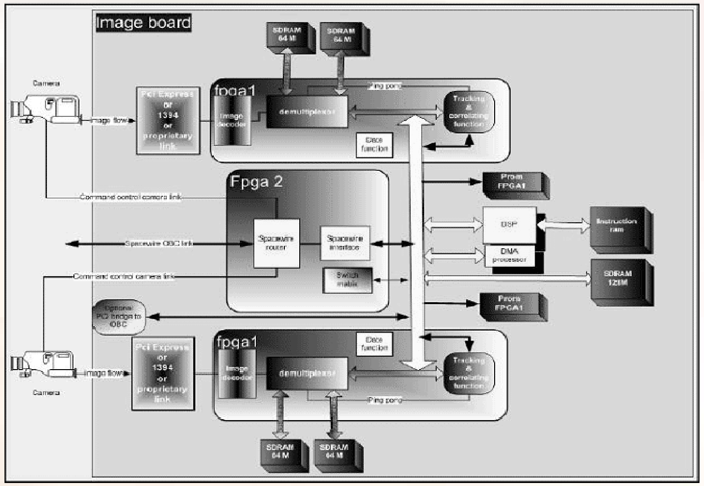
Multi-mission Vision based Navigation System (VisNav)

Objectives

- Vision-based navigation system modular architecture suitable for planetary landing, space rendezvous, interplanetary navigation and rover applications

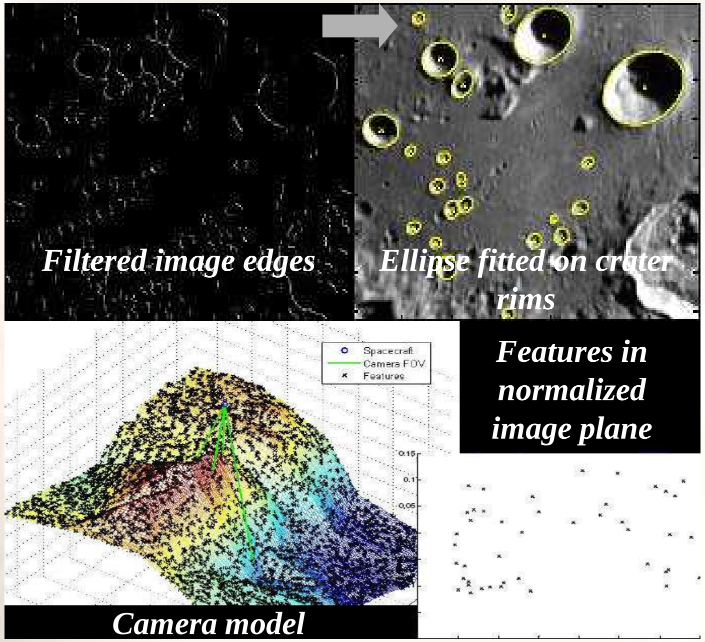
Modular architecture consisting of:

- camera optics/electronics
- IP board
- OBC (navigation software)



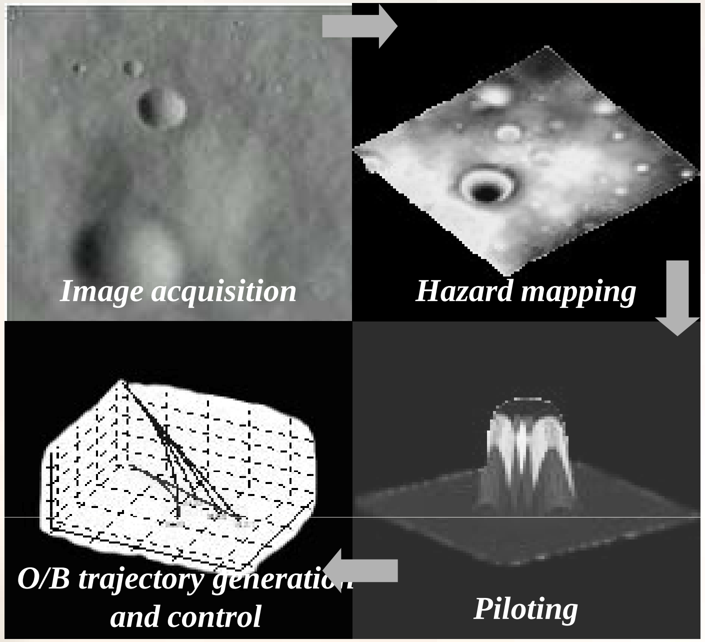
VisNav Image Processing (IP) board functional architecture – Rover as an example

- **Objectives**
  - Absolute position and surface-relative velocity using global/local features during the proximity operation of a planetary mission
  - Validated the candidate algorithms (TRL: 3) for both Moon and NEO descent & landing scenarios



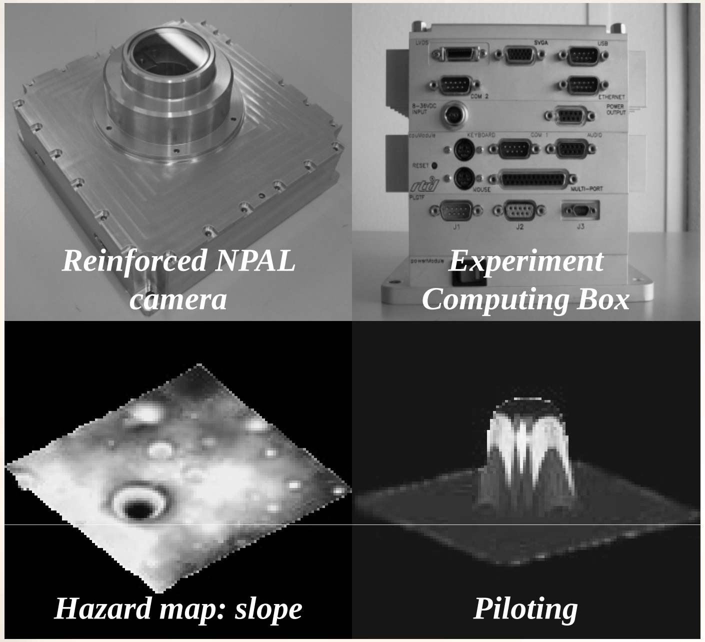
Vision based Relative Navigation Framework

- **Achievements**
  - Designed a complete hazard avoidance system, and successfully tested in VBNAT for Mercury landing scenarios
  - Demonstrated IP algorithm robustness: meaningful hazard maps obtained in bad illumination conditions
  - Designed and validated an E-guidance law with re-targeting capability (fuel, visibility, thrusters and trajectory constraints)
  - Assessed real-time performances of IP and GNC critical functions
  - TRL: 3
- **Main features**
  - Uses NPAL camera as main sensor for HM
- **Next step**
  - HA demonstrator experiment development



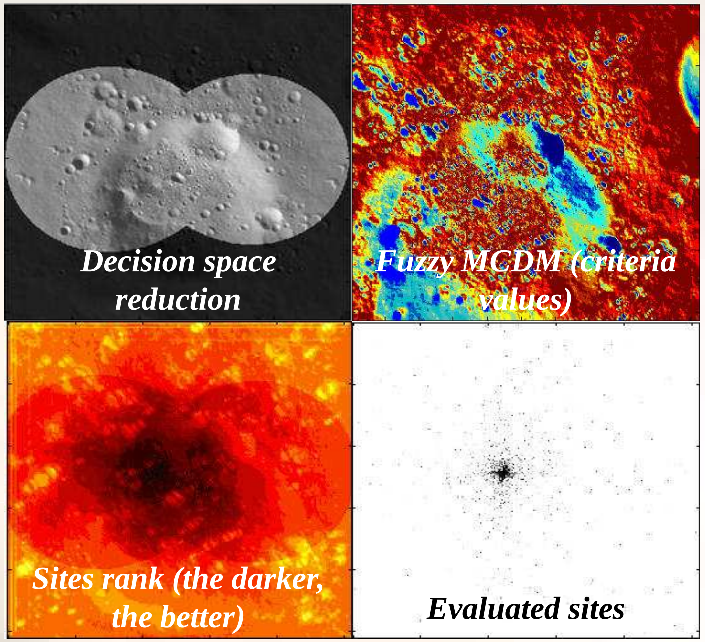
Vision based Hazard Avoidance System Experiment

- **Objectives**
  - Prepare a vision based Hazard Avoidance demonstrator experiment
  - Perform PLGTF field tests in Morocco
  - TRL: 5-6
- **Main Features**
  - Navigation and HA embedded SW running on two dedicated computer boards
  - Reinforced NPAL camera + Experiment Computing Box (ECB) + imaging recorder
- **Achievements/Status**
  - Ongoing robustness performance consolidation of the HA demonstrator functional prototype (Lunar Lander scenario)



Intelligent Mathematical Processing for Efficient Site Selection

- **Objectives**
  - Formalize, develop and implement a novel fuzzy multi-criteria decision making (MCDM) algorithm for safe landing site selection
  - Validate the baseline MCDM algorithm for both Mars and Moon landing scenarios
  - Carry out performances benchmarking against previous reference solutions
- **Main Features**
  - Genetic approach implementation required for CPU load constraints

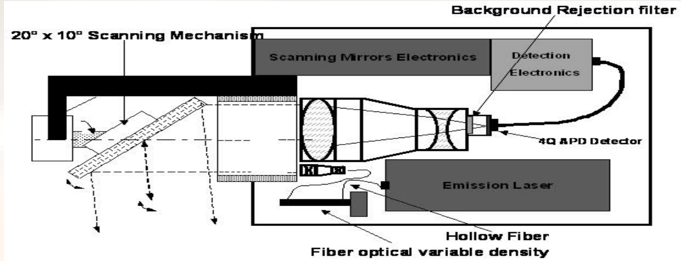


Lidar based GNC for Safe Landing (LiGNC)

- **Achievements**
  - Scanning Lidar functional specifications and preliminary design
  - Developed reusable guidance and control algorithms
  - Adapted PANGU to Lidar and radar doppler sensors
  - Demonstrated the end-to-end performance of a Lidar-based GNC system for safe landing (Mars)
  - Assessed real-time performances of IP and GNC critical functions
  - TRL: 2-3

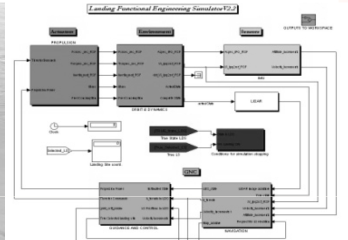
- **Main features**
  - Scanning Lidar, inc. 3D map generation and motion compensation algorithm

- **Next step**
  - Demonstrator experiment development



Lidar instrument concept overview

Slope map from PANGU lidar model



High fidelity end-to-end simulation

Imaging Lidar Technology Breadboard (ILT)

Objectives

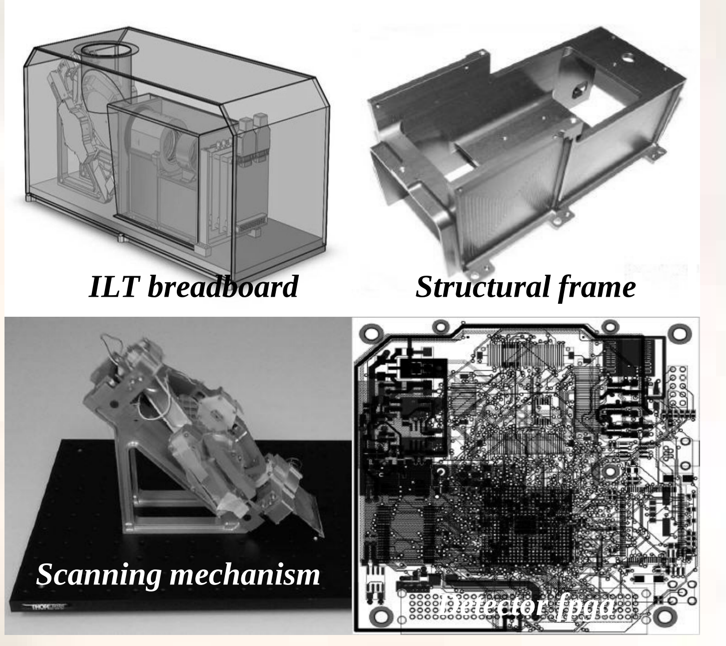
- Develop, demonstrate and validate novel technologies for imaging lidar sensor (landing, rendezvous and rover applications)
- Manufacture, integrate and test (static/dynamics) an Imaging Lidar breadboard
- TRL: 4

Achievements/Status

- Manufactured Imaging Lidar structural frame, scanning mechanism, PCB board, detector FPGA, etc.
- Performed functional and interfaces tests of the power board
- Difficulties with the manufacturing of the 1x256 array detector

Next Steps

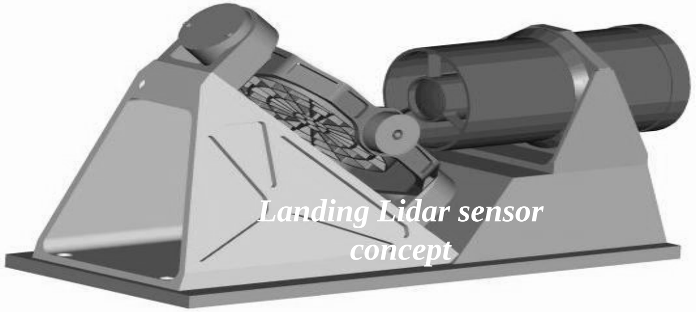
- PLGTF field tests
- Landing Imaging Lidar Sensor EM: Design Phase



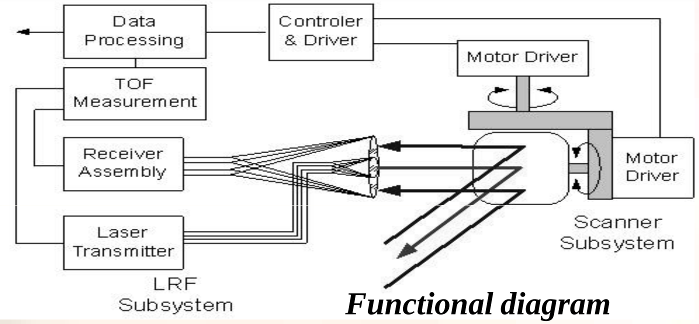
ILT breadboard — *Structural frame* — *Scanning mechanism* — *ector fpga*

Imaging Lidar Technology Breadboard (ILT)

- **Objectives**
  - Develop, demonstrate and validate novel technologies for imaging lidar sensor (landing, rendezvous and rover applications)
- **Achievements**
  - Selected Rendezvous as reference application. On-going integration and testing of a BB model
  - For Mars landing application (TRL: 1-2)
    - Defined 3 concepts and selected a reference design (HW/SW) concept
- **Main features:**
  - Characteristics: multi-channel
  - Transmitter: Fiber laser 4 x 4 kW @ 1550 nm
  - Receiver: 1 x 80 mm aperture, 4-elements InGaAs APDs
  - Scanning: gimbal-mounted mirror, FoV: 20° x 20°
  - Mass: 3.2 kg (OHU) + 8.5 kg (EU)
  - Power: < 100 W

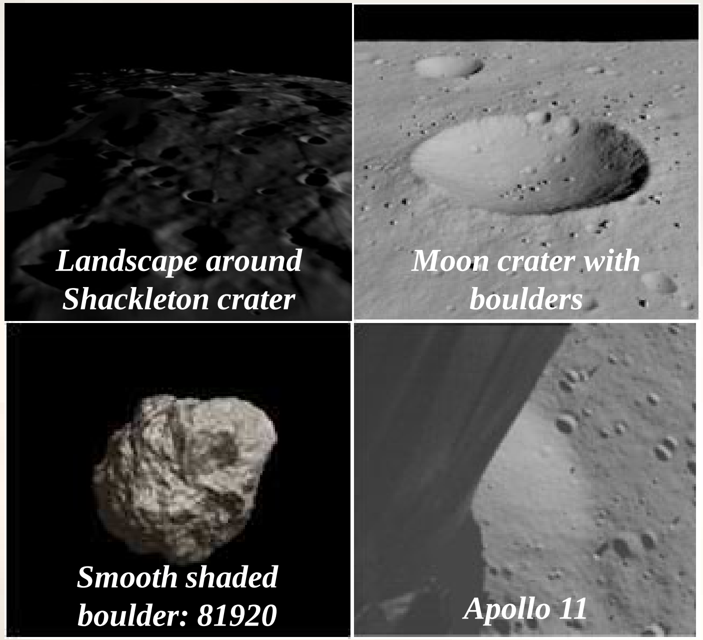


Landing Lidar sensor concept



Functional diagram

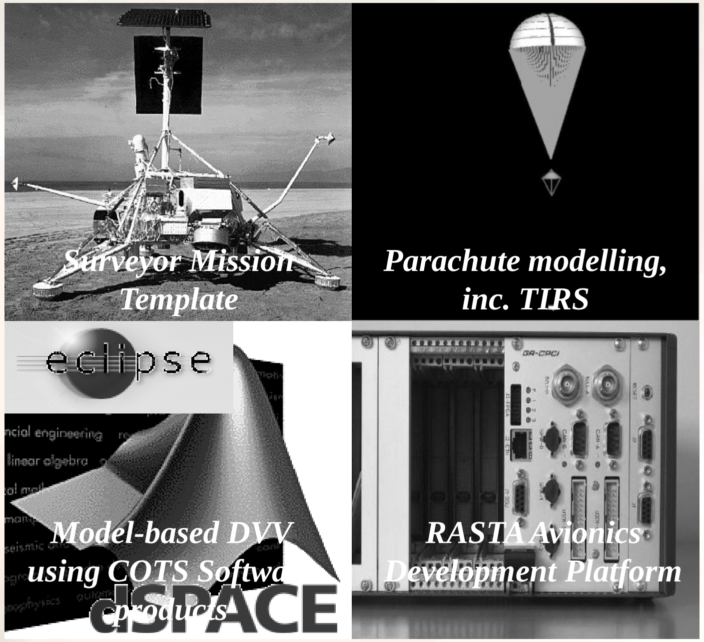
- **PANGU: Planet and Asteroid Natural scene Generation Utility**
- **Objectives of recent enhancement:**
  - Enhanced lunar small scale features: small craters and boulders
  - Lunar Pole South DEMs from Clementine and radar data
  - Improve lunar surface reflectance
  - Add ground proximity effects: lander shadow and dust from thrusters
  - Better (and faster) rendering / Improved GUI



- **Achievements/Status**
  - European asset as Image Generator for vision based GNC
  - Lunar South Pole DEMs delivered

Entry And Guidance Landing Environment (EAGLE)

- **Objectives**
  - Simulation framework for the design, development and testing of (E)DLS GNC systems
  - Reference mission templates: Pathfinder, MER, ExoMars, MSR, EVD and Surveyor
- **Main Features**
  - Model-based development, validation & verification based on open source and COTS software products
  - Support to 4-steps verification process: MIL, SIL, PIL and HIL
  - Avionics test bench based on dSPACE modular hardware and RASTA



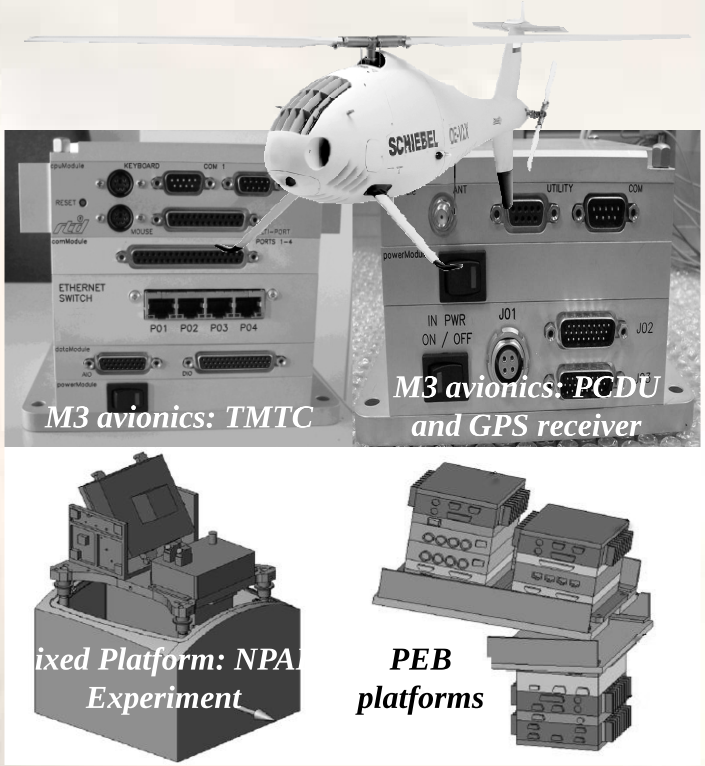
Precision Landing GNC Test Facility (PLGTF)

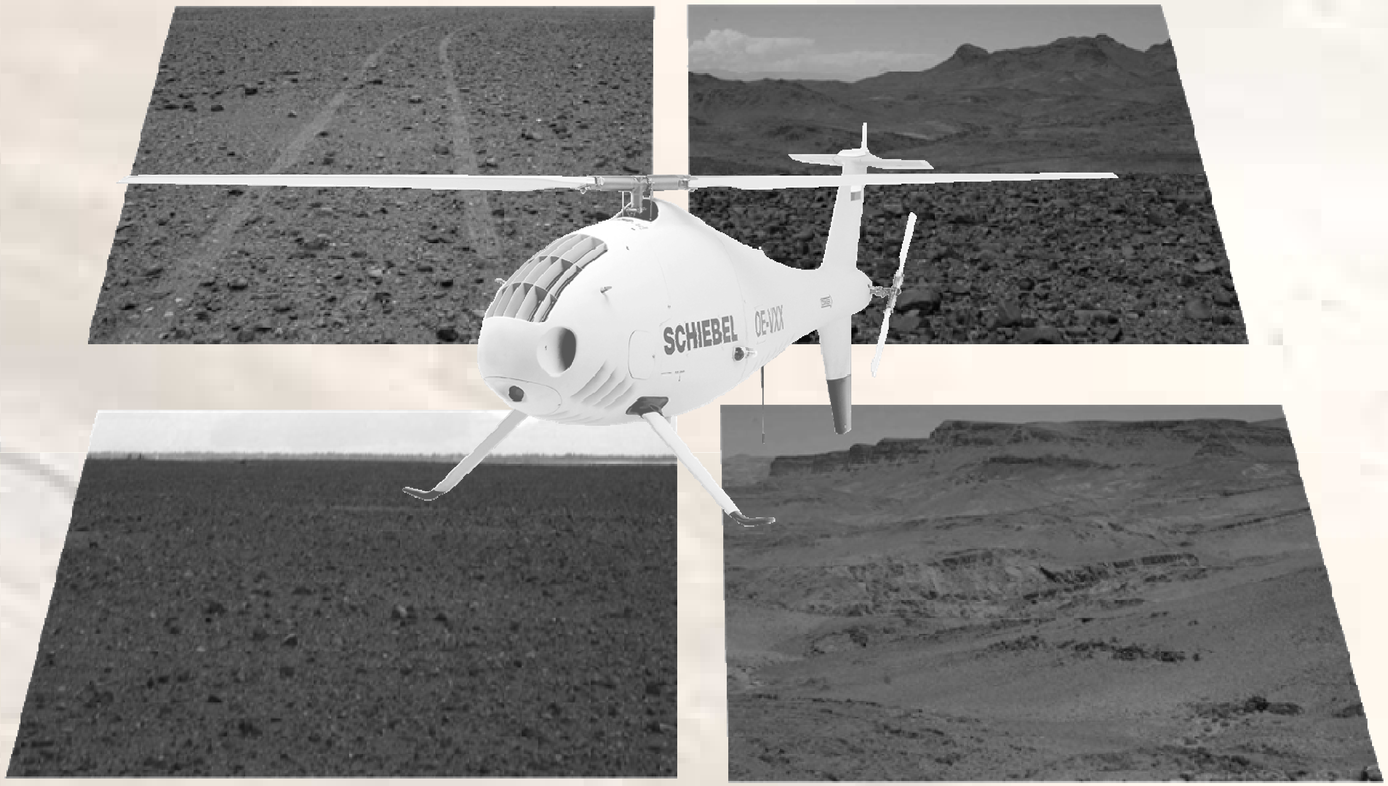
Objectives

- Develop a cost effective landing GNC test facility emulating a lander vehicle dynamics
- Increase planetary landing GNC Technology Readiness Level up to 5-6
  - Vision-based navigation system
  - Lidar-based navigation system
  - Hazard avoidance system

Main Features

- Helicopter UAV for supporting scaled Martian and Moon landing sequences
- PC/104 stackable PCI modules from RTD: CPU, GPS receiver, etc.





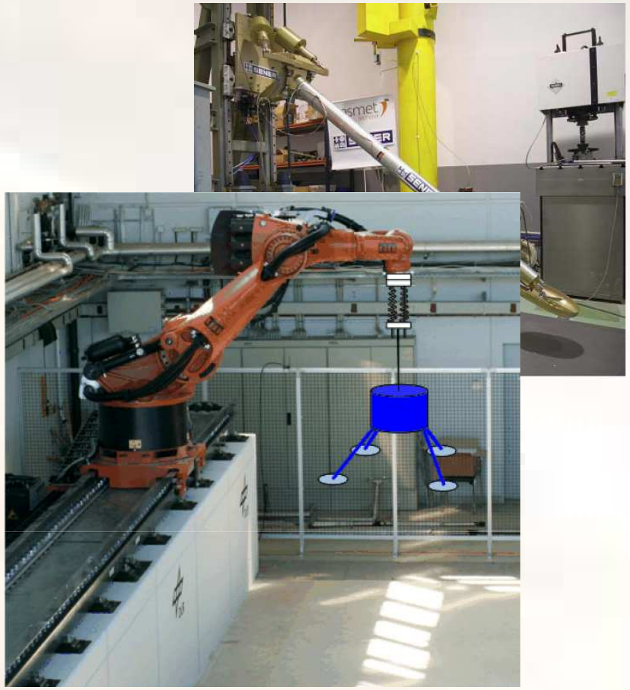
Selected Mars (left) and Moon (right) landing site for the validation of the NPAL navigation system in Morocco

Scalable EDL GNC & Avionics System Demonstrator

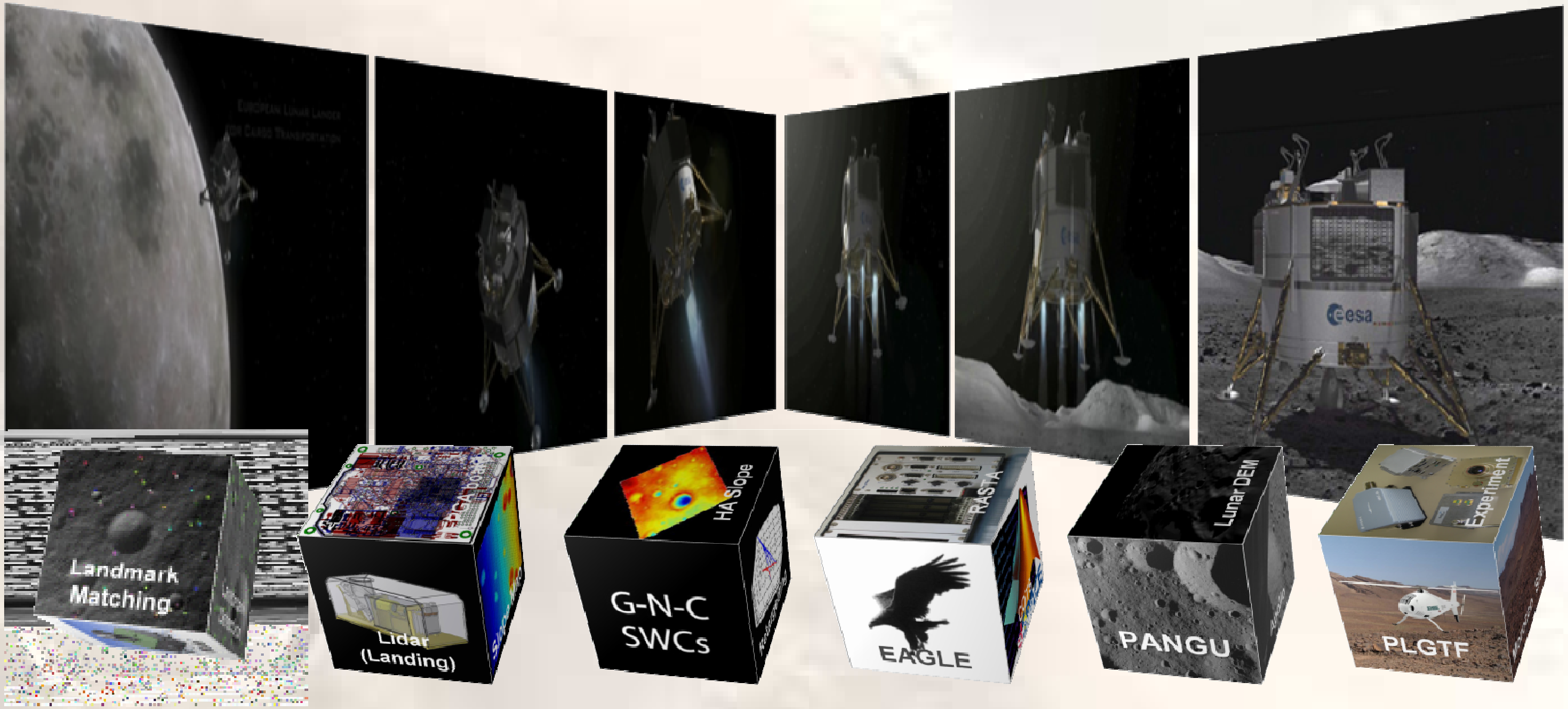
- **Objectives**
  - Develop and mature to TRL 5 a scalable Autonomous Guidance, Navigation & Control (AGNC) system capable to bring safely and precisely valuable assets on the lunar surfaces
  - Develop G-N-C building blocks, inc. FDIR and in-flight calibration functions
  - Enhance EAGLE model-based DV&V process and associated chain tool
  - Develop a complete demonstrator of the reference (E)DL AGNC system
- **Main Features**
  - AGN&C system capability for both optical and non-optical measurements

Landing System Development

- **Background**
  - Lightweight landing leg for the MSR mission, with testing of a single leg
- **Objectives**
  - Design a landing system based on legs using Lunar Lander as reference mission
  - Conduct pre-development testing, e.g. at material/component/simplified system level, to confirm feasibility
  - Design, manufacture and test a complete breadboard (with all the legs attached to the platform) in support of design and modelling activities (e.g. LAMA facility)
- **Main Features**
  - Stepwise approach to build confidence in methodology, design choices and validation of the models



Lunar lander GNC technologies summary



VisNav: Landing, RV, IP and Rover

Lidar based Navigation Systems

Reusable GNC/HDA SWCs

EDLS DVV Framework

Synthetic Scene & DEMs

Dynamics Test Facilities

Technology Building Blocks (TRL 6 by 2013)

Summary and conclusions

- A mission to an airless body represents a challenge for GNC design and technology development planners.

- Needs and gaps:
  - Close interaction Mission/System and GNC design, adopting results of innovation in methods and techniques
  - Development and availability of validated set of models
  - Need of investment in test facilities and ground demonstrators accessible to major stake holders in a programme
  - Real planetary imagery is essential for GNC design validation
  - Possible use of fligth data from one mission to another for tuning and validation of models and prediction tools.

- Conclusion:
  - A relevant effort has been devoted by ESA and its industry in the last years to close most critical technology
  - The analysis performed detects a high level of compentence and GNC technology maturity to timely achieve the TRL6 in 2013 for the Lunar Lander implementation decision.